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Urban Food Systems: Applying Life Cycle Assessment in Built Environments and Aquaponics

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Abstract

As the building sector faces global challenges that affect urban supplies of food, water and energy, multifaceted sustainability solutions need to be re-examined through the lens of built environments. Aquaponics, a strategy that combines recirculating aquaculture with hydroponics to optimize fish and plant production, has been recognized as one of "ten technologies which could change our lives" by merit of its potential to revolutionize how we feed urban populations. To holistically assess the environmental performance of urban aquaponic farms, impacts generated by aquaponic systems must be combined with impacts generated by host envelopes. This paper outlines the opportunities and challenges of using life cycle assessment (LCA) to evaluate and design urban aquaponic farms. The methodology described here is part of a larger study of urban integration of aquaponics conducted by the interdisciplinary research consortium CITYFOOD. First, the challenges of applying LCA in architecture and agriculture are outlined. Next, the urban aquaponic farm is described as a series of unit process flows. Using the ISO 14040:2006 framework for developing an LCA, subsequent LCA phases are described, focusing on scenario-specific challenges and tools. Particular attention is given to points of interaction between growing systems and host buildings that can be optimized to serve both. Using a hybrid LCA framework that incorporates methods from the building sector as well as the agricultural sector, built environment professionals can become key players in interdisciplinary solutions for the food-water-energy nexus and the design of sustainable urban food systems.

Keywords: open, life cycle assessment, urban agriculture, aquaponics

Introduction

Urban environments rely on an interdependent network of food, water and energy that stretches beyond city limits to sustain its inhabitants [1], [2]. In 2006, 70-80% of all environmental impacts incurred by EU-25 countries originated in three areas interconnected by their use of food, water and energy - food and drink consumption, housing, and private transport [3]. Agriculture in particular is a key driver of climate change, water depletion, habitat change and eutrophication [4], exacerbated by the need for food production to increase by at least 70 percent to meet demands by 2050 [5]. In recent years, urban agriculture has gained momentum as a potential alternative to traditional food systems - aiming to reduce the distance from farm to consumer, recycle waste streams, and provide food security to underserved populations [6].

While urban agriculture has gained significant ground through small-scale recreational and educational uses, operating large-scale agricultural businesses within city bounds is still a young practice that often relies on technological innovation to produce market-competitive crops. In particular, aquaponics has been recognized as one of "ten technologies which could change our lives" by merit of its potential to revolutionize how we feed urban populations [7]. In a coupled aquaponic system, combining recirculating aquaculture with hydroponics

optimizes nutrient and water flows for simultaneous production of aquatic animals and plants. With the help of nitrifying bacteria, nitrogen-rich wastewater from aquaculture tanks supplies nutrients for growing crops, which then filter the water to a state where it can be safely returned to the beginning of the cycle [8]. While there are many ways to practice aquaponics using a wide range of aquatic animal and crop species, this paper will primarily refer to systems that contain fish (often tilapia) and leafy greens (lettuce, kale, and various herbs). As aquaponic

systems attempt to simultaneously balance the complex needs of fish and plants, they are often practiced in controlled environments such as greenhouses, which offer a degree of protection from unfavorable climate conditions and pathogens. The relationship between the aquaponic system and the surrounding envelope has the potential to be beneficial for both - a building-integrated aquaponic farm can improve host building performance, while a well-designed envelope can raise farm productivity [9], [10].



Figure 1 Ouroboros Farms, Half Moon Bay, CA

The urban integration of aquaponics is a multifaceted sustainability strategy that can simultaneously address water use, food production, energy use, and built

environment performance in cities. To holistically evaluate how urban aquaponic farms perform in comparison to existing food systems and built

environments, life cycle assessment can be used as a systematic methodology that is common to both architecture and agriculture; it has potential to bridge the gap between the two in the pursuit of sustainable cities.

Life cycle assessment (LCA) enables researchers in different fields to understand environmental impacts incurred by a product for the purpose of improving product performance and informing decision-makers and consumers. LCA is a standardized method regulated by the International Standards Organization [11, p. 2006], [12, p. 2006]. An ISO-compliant LCA study contains four phases - goal and scope definition, inventory analysis, impact assessment and interpretation (see *Figure 2*). In order to maintain comparability, LCAs must define a *functional unit* as the object of analysis - a unit including quantity, quality and duration of the product or service provided [13]. The methodology framework is intentionally flexible to accommodate assessments of different industrial processes and product types.

LCA is an attractive tool for both built environment and agriculture professionals because it is comprehensive - the life cycle of each system component is documented using emission data, from manufacture to operation and eventual disposal. Recently, some LCA methods for assessing environmental impact have been integrated with parametric design tools already familiar to building professionals through software such as Tally for Revit or One-Click LCA [14], [15]. This paper outlines the opportunities and challenges of using life cycle assessment to evaluate urban aquaponic farms with the aim of motivating collaboration between built environment professionals and aquaponic experts in the interest of assessing the food, water and energy implications of scaling up aquaponic production in cities.

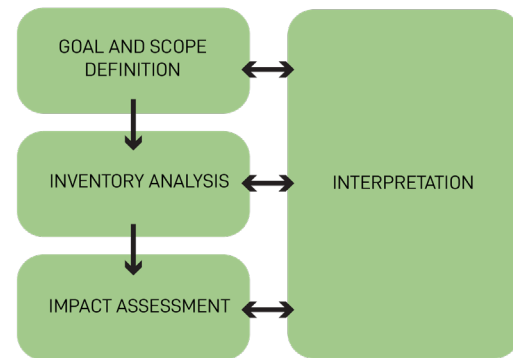


Figure 2 General LCA framework (adapted from ISO 14040:2006)

Literature Review

LCA in the building industry

In the building sector, LCA is used to evaluate both individual construction components and whole building systems [16]. The life cycle of buildings consists of material extraction, component manufacture, construction, operation and eventual demolition. Operational impacts caused by maintaining occupant comfort throughout the lifespan of the structure tend to outweigh embodied impacts caused by component manufacture and assembly in conventional buildings; although embodied impacts of high-performance buildings can be significantly higher [17]. Due to the dominance of the operational phase, LCA in the building sector is often used to detect opportunities for optimizing energy use. In both hot and cold climates, climate control systems often account for a significant proportion of total energy costs. Building professionals can take advantage of LCA as a design tool to make informed material and configuration decisions that affect the operation of each project throughout its lifespan before it is constructed [13].

LCA in the agriculture industry

The agricultural sector uses LCA to legitimize ecolabeling certain food products and pinpoint optimization opportunities in growing, harvesting, processing and distributing food to consumers. The life cycle of an individual crop is often considered from seed to harvest, omitting the preparation and disposal of food by

consumers due to uncertainty. An assessment of a particular crop can include soil preparation, planting, irrigation, fertilizer and pesticide application, harvest, storage and transport. The application of chemicals to reduce risk is particularly significant in the life cycle of a crop due to inadvertent leaching of toxins into the surrounding environment that can cause erosion and eutrophication [18].

LCA Challenge	Building sector¹	Agricultural sector²
Determining functional unit	Buildings have multiple functions	Agriculture often produces multiple co-products at once
Determining site-specific impacts	Lack of local data	
Representing model complexity	Many non-standard components	Variable practices
Acknowledging scenario uncertainty	Long lifespans	Seasonal variability
Locating data	Lack of data on recycling	Lack of data on fertilizer dispersal

¹ Adapted from [16]

² Adapted from [19]

Table 1: Common challenges in building and agricultural sector LCA

LCA in aquaponics

Since aquaponics is a young, yet rapidly-growing field, the author was able to find only seven published studies of environmental impact in aquaponics that use the LCA approach. Most focus on small research facilities, and exclude the built envelope of the aquaponic farm from the scope of the assessment.

A study performed at the University of Ca' Foscari in Venice, Italy used LCA to compare impacts caused by two simulated aquaponic farms located in greenhouses in Northern Italy - one using deep water culture (also known as the RAFT technique), in which plant roots are submerged in troughs containing nutrient-rich water and one using a media-filled bed system (MFBS), where water is pumped through beds filled with substrate such

as clay pellets [20]. More recently, a simulated small-scale aquaponic system was compared to traditional tilapia and lettuce production [21]. On the smallest scale, a classroom aquaponic kit was assessed and compared to the impact of other educational supplies [22]; on the largest, an LCA of an outdoor 500 m² aquaponic research facility on the U.S. Virgin Islands was conducted [23]. Using collected data from a research facility, a small aquaponic system was compared to a hydroponic system of the same size in a greenhouse located nearby Lyon, France [24]. Similarly based in collected data, an earlier LCA attempted to simultaneously address environmental impact and profitability of an aquaponic system in Iowa [25]. Finally, a dissertation from the University of Colorado compiled a life cycle assessment based on data from the operation of a 297 m² aquaponic system 'Flourish Farms', a part of the GrowHaus urban food hub

in Denver [26]. The compiled comparison of previous aquaponic LCA literature can be found in *Table 2*.

Study	Year	Impacts considered										Farm enclosure size	Farm enclosure type
		Abiotic Depletion	Global Warming Potential	Acidification	Eutrophication	Ionizing Radiation	Mineral Resource Scarcity	Water Consumption	Human Toxicity Potential	Energy Use	Land Competition		
Xie and Rosentrater	2015		●					●		●		288 sf	Greenhouse
Forchino et al.	2017	●	●	●	●							430 sf	Greenhouse
Boxman et al.	2017		●	●	●			●	●	●	●	5,381 sf	Outdoor
Hollman	2017		●					●		●		3,196 sf	Greenhouse
Cohen et al.	2018		●		●	●	●	●				None	None
Maucieri et al.	2018	●	●	●	●							None	None
Jaeger at al.	2019		●	●	●			●		●	●	2,421 sf	Greenhouse

Table 2: Comparison of previous aquaponic LCA studies

Existing literature on aquaponic LCA reflects the early stage of research in this field - most studies are based on life cycle inventories constructed from hands-on data, collected at a small research facility. However, to effectively assess how aquaponics will perform in the complex urban fabric of North American and European cities, other enclosure types besides greenhouses need to be assessed and incorporated into the LCA methodology. Integrating practices from both the building and the agricultural sector in LCA is essential to assessing the sustainability of future urban food production systems such as aquaponics.

Hybrid LCA methodology

In order to assess the environmental footprint of a commercial-scale urban aquaponic farm, CITYFOOD intends to conduct an LCA. The following outline describes the steps that will have to be developed to conduct a hybrid LCA study that bridges built environment expertise with aquaponic knowledge. This approach follows recommendations laid out in ISO 14040:2006 and ISO 14044:2006 [11], [12].

Goal and scope

The goal and scope phase of an LCA sets the trajectory of the study by modeling the selected product system as a series of discrete unit processes, defining the functional unit, and clarifying data assumptions and limitations. A

prototypical commercial aquaponic farm system can be described by a process flow diagram represented in *Figure 3*.

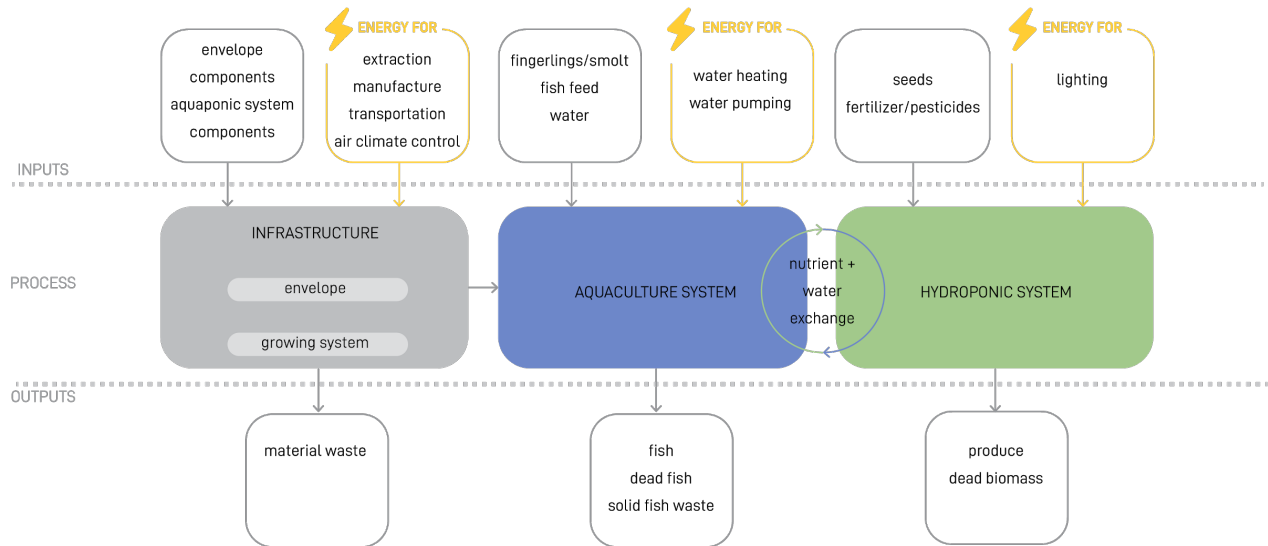


Figure 3 Process flow diagram describing an aquaponic farm system.

Many aquaponic studies done by aquaculture and horticulture scientists omit infrastructure - materials used for tanks, pipes, water troughs, surrounding structure and cladding in each farm. However, including infrastructure and enclosure is essential to understanding the impacts incurred by aquaponic farms in most temperate and colder climates, where aquaponic systems need a controlled climate to operate year-round. Infrastructure occupies a unique place in the process flow diagram, since it is both an ongoing process (requiring energy to maintain the interior climate, and occasional material inputs for component repair and replacement) and an input for the operation of the aquaponic system. Understanding that the contribution of the building sector

to global environmental impacts is comparable in magnitude to the agricultural sector, envelope design for urban aquaponic farms becomes an opportunity for optimizing overall environmental performance of urban food systems.

Determining a functional unit is a challenge in both building and agricultural sector LCA (see *Table 1*). To assess the aquaponic farm, the LCA practitioner needs to first specify the intended application for the study. To compare results to conventional aquaculture, 1 ton of live-weight fish produced for the intended duration of the farm may be used [23]. For comparing aquaponics in terms of horticulture, fish may be treated as a co-product

and the functional unit may be set to 1 kg wet-mass crop harvested [20]. To compare the performance of an aquaponic farm to other types of enclosures, 1 square foot of farm operated for the intended duration may be analyzed - however, accounting for the production of both fish and plants in the facility poses an impact allocation challenge which may be solved through system expansion [28].

Inventory analysis

The inventory analysis phase of an LCA involves quantifying inputs and outputs defined in the scope of the study through data collection about each resource flow within the system. Although in a realistic scenario all resource flows are connected within the aquaponic farm, collecting and analyzing data will be described in terms of infrastructure, aquaculture and hydroponic inputs and outputs.

Infrastructure inputs and outputs - This category of resource flows includes material and energy expenditures for constructing and maintaining a farm envelope and aquaponic equipment. Building-specific LCA databases and tools can be used to obtain unit process flow data for material extraction, component manufacture and disposal. Some examples include Athena Impact Estimator, BEES, and One-Click LCA; for an extensive list of building-specific and generic LCA tools and databases that support built environment studies, see the report generated by the Efficient Buildings study at the European Commission Joint Research Centre [29, p. 2]. To obtain material unit process data to represent aquaponic equipment, generic LCA tools and databases such as OpenLCA, OpenLCA Nexus, GREET, USLCI Database, GaBi, ecoinvent and SimaPro can be used. For transportation data within the U.S., the Argonne GREET tool can apply.

As a comparison of multiple farms in Australia shows, high-tech soilless farm LCA results correlate strongly with energy use [30]. If interior energy needs of the aquaponic system are carefully calibrated to exterior climate pressures, overall energy expenditures for operating the farm can be reduced. Species selection in the horticultural component of aquaponic systems determines the climate setpoint for the entire enclosure - for example, head lettuce thrives in cooler temperatures (60-70°F), whereas tomatoes grow most efficiently when the surrounding environment is warmer during the day (70-80°F) [31]. This is an important point of interaction between the aquaponic system and the surrounding envelope – selecting a crop that is better-adapted to exterior climate conditions can reduce the overall energy demand for the farm enclosure.

The selection of climate control systems and building assemblies also contributes to the energy demand of each aquaponic farm, and simultaneously influences farm productivity. Some aquaponic farms employ evaporative cooling or fog cooling systems in place of energy-intensive air conditioning; alternatives to forced-air heating also exist, such as passive solar design and radiant floor heating. Considering energy expenditure for establishing climate control, cladding material choice becomes important - whereas aquaponic farms in transparent enclosures can benefit from solar light and heat, opaque farms in warehouses can save energy by blocking heat loss with highly-insulated envelopes. These architectural decisions influence the productivity of the aquaponic farm – the ability of the cladding material to transmit sunlight directly impacts the availability of photosynthetically-active radiation (PAR) for plants' growth, and the temperature and humidity levels maintained by heating and cooling systems impact the rate of evapotranspiration and biomass accumulation in plants.

One unique consideration for aquaponic farms is the need to control humidity. The addition of fish tanks into the enclosure raises humidity, which both supports better plant growth and introduces a higher risk for the spread of pathogens [34]. In future LCA studies of aquaponic farms, energy expenditure for humidity control and associated temperature adjustments may play a more significant part than in hydroponic alternatives.

Energy-modeling tools such as EnergyPlus can be applied to calculate overall energy expenditures for climate control in aquaponic farms [32]. Additional energy exchanges from rearing fish and plants have been modeled under the project Virtual Greenhouse [33].

Aquaculture inputs and outputs - This category includes material and energy flows needed to grow fish.

Agricultural LCA databases such as Agribalyse and Agri-footprint can be used to obtain limited data on fish feed unit processes and smolt production; no dedicated LCA database for fish production exists. Much like crop species, fish species selection determines the setpoint for the entire system, since different species thrive at different temperatures [9].

In most aquaponic systems, liquid fish waste is treated as an asset since it provides nutrients for crop growth; however, solid fish waste is disposed from the system. There is little data on the treatment of solid fish waste, so it is difficult to determine its relative environmental impact. This may change - aquaponic researchers propose reintroducing solid fish waste into the process of the aquaponic farm as a valuable asset by remineralization or the use of anaerobic digesters [35], [36].



Figure 4 Urban Organics, St Paul, MN

Hydroponic inputs and outputs - This category of resource flows includes material and energy flows needed to grow plants. Limited data on seed production is available through agricultural LCA databases as well as generic ones (Agribalyse, Agri-footprint and USLCI). Commercial-size aquaponic facilities often supplement nutrients derived from fish waste with synthetic fertilizers in order to ensure a stable rate of crop production. Data on generic fertilizer production can be similarly accessed through agricultural LCA databases, although finding unit process flow data for the production of liquid fertilizer solutions specific to soilless growing systems poses a challenge.

Energy required for lighting is largely dictated by the needs of the cultivated crop and the enclosure of the farm. Operating a farm in an indoor, insulated environment may reduce the need for climate control energy expenditure, but necessitates the installation of artificial lighting arrays. The energy trade-off between operating climate control and lighting in different urban farm designs can have a significant impact on the overall environmental performance of the farm [37].

Impact assessment

Most previous LCA studies of aquaponics have considered global warming potential, eutrophication, energy use and water use as impact categories (see *Table 2*). From the built environment standpoint, energy use is a highly valuable impact category to include in an LCA study, since the existing building stock in the United States is responsible for 40% of national energy consumption and 72% of national electricity use [38]. Water use is another impact category that is relevant for both sectors - in a recent study analyzing the water impact of a typical residential building in Australia over a 50-year lifespan, direct water consumption accounted for 12% of the inhabitants' demand, whereas the water

embodied in producing consumable goods such as food represented 46% [39]. If water-recirculating growing systems like aquaponics tap into alternative urban water sources such as rainwater and greywater from residential use, the cumulative water footprint of living in the city could be reduced both due to diminished direct water demand and diminished implicit water demand embodied in food production. Some impact calculation methodologies available to LCA practitioners in the building and agricultural sector include the CML method, ReCiPe midpoint and endpoint approaches, and TRACI, among others [40].

Interpretation

Understanding the implications of infrastructure design for growing system efficiency is the next step in realizing urban aquaponic farms that are competitive and sustainable. The challenges that lie ahead for built environment professionals interested in using LCA to design sustainable urban food systems include:

- (1) Energy modeling - using a variety of simulation tools from both built environments and agriculture to represent the climate control and lighting energy expenditures in a large-scale farm.
- (2) Data availability - secondary inventory data for aquaculture and soilless horticulture is often lacking in open-source LCA databases.
- (3) Data validation - as aquaponics is a young field, simulation results will have to be compared to real performance data from farms to be validated.

Previous hybrid LCA work focused on a hydroponic rooftop greenhouse located in Barcelona serves as a good example of incorporating data from the built environments and horticulture to develop a comprehensive assessment of a new sustainable technology [41].

Conclusion

Life cycle assessment is a valuable tool for both the agricultural and building sectors to address global challenges in the sustainable management of food, water and energy. Quantifying the impacts of multidisciplinary solutions such as urban aquaponic farming requires expertise from built environment professionals. For architects, engineers and planners looking for sustainable solutions, constructing LCA studies that bridge the building sector with agriculture can result in unexpected discoveries of synergies within urban resource flows. In this way, new hybrid LCAs can become not only a retrospective assessment tool, but also an aid for decision-making during the design stage.

Investigating the relationship between innovative food production and building construction through hybrid LCAs that incorporate multidisciplinary knowledge can alleviate the environmental impact of both. Although urban aquaponic farms are currently few and far between, results from existing LCA studies are promising. Scaling up aquaponic farms to a commercially-viable size within cities can be an exciting step towards sustainable urban food systems which prioritize closing resource loops.

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